Tetrahedron 70 (2014) 9381–9386

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Oxidation of alkenes with non-heme iron complexes: suitability as an organic synthetic method

David Clemente-Tejeda, Francisco A. Bermejo *

Departamento de Química Orgánica, Universidad de Salamanca, 37008 Salamanca, Spain

ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form 2 October 2014
Accepted 16 October 2014
Available online 22 October 2014

Keywords:
Oxidation
Iron catalysis
cis-Dihydroxylation
cis-Jasmone
trans-Jasmone

ABSTRACT

In the course of a preliminary study to determine the preparative value and the synthetic applications of the non-heme iron(II) complexes Fe(**bpmen**)$(OTf)_2$ and Fe(**tpa**)$(OTf)_2$, in particular the oxidation of alkenes by using hydrogen peroxide as the terminal oxidant, we have found significant differences in catalyst behavior. After several attempts it was clear that the preparative relevance of the oxidation processes was linked to the concentration of the catalyst and optimal results were obtained when the concentration value was 5 mol %. At that concentration, the Fe(**bpmen**)$(OTf)_2$ catalyst mostly gave rise to mixtures of the epoxide and the *trans*-dihydroxylation products formed by water-assisted hydrolytic cleavage of the epoxides. Furthermore, the use of the tripodal ligand **tpa** led to *cis* dihydroxylation products. When deactivated olefins were used as substrates for the oxidation reaction, the *cis*-diols were obtained exclusively, although with modest conversions, regardless of the catalyst used.

1. Introduction

Current methodology to achieve the catalytic *cis*-dihydroxylation of alkenes with preparative significance in organic synthesis is mainly focused on osmium and ruthenium compounds. However, some of the reagents used for this purpose are expensive, rather volatile and toxic. Accordingly, the development of alternative catalysts for the *cis*-1,2-dihydroxylation of alkenes is very challenging.[1]

Inspired by the active site of iron oxidation enzymes, chemists have designed a wide variety of complexes that could mimic these metalloenzymes functionally, with the final goal of designing catalysts to achieve the oxidation of alkanes[2–16] and alkenes.[17–33] It has been seen that the most effective non-heme iron catalysts are those possessing nitrogen-based tripodal or linear tetradentate ligands, such that two *cis* labile sites available for coordination with exogenous ligands become available (Fig. 1). During the last twenty years, the preparation of a series of organic ligands that incorporate the key features of the non-heme active iron site of the Rieske dioxygenases, bacterial enzymes that perform the enantioselective *cis*-dihydroxylation of arene and alkene double bonds, has led to the characterization of several non-heme iron complexes and their application to dihydroxylation processes.[34–39] However, most of this effort has been developed by bioinorganic groups mainly interested in understanding enzyme mechanisms.[40]

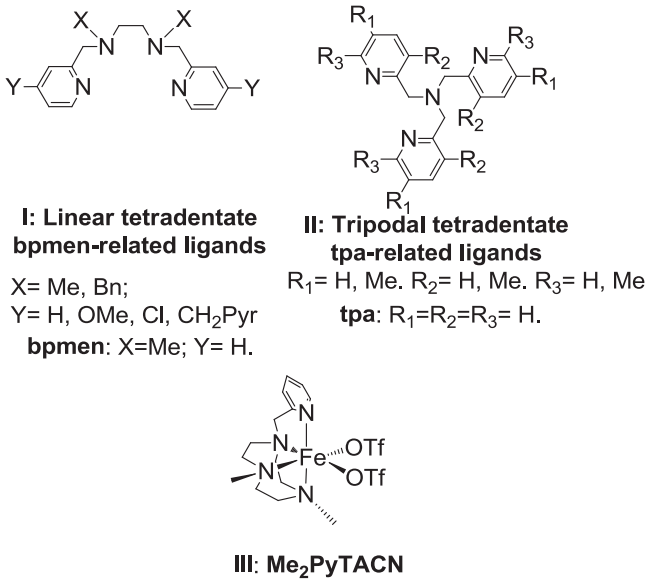


Fig. 1. Examples of the organic ligands used in the non-heme iron catalysis.

In an investigation of the oxidation of alkenes by non-heme iron enzyme mimics[41] in the course of a preliminary study to determine

* Corresponding author. Tel.: +34 44 923 294481; e-mail address: fcobmjo@usal.es (F.A. Bermejo).

http://dx.doi.org/10.1016/j.tet.2014.10.037
0040-4020/

the preparative value and synthetic applications of the non-heme iron complexes derived from the above-mentioned linear nitrogen-based tetradentate ligands, in particular the oxidation of alkenes by using hydrogen peroxide as the terminal oxidant, we focused our interest on bpmen iron(II) complexes and their capacity to oxidize steroids, monoterpenes and polycyclic aromatic hydrocarbons.[42–44]

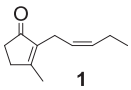
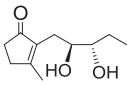
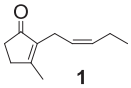
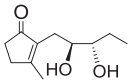
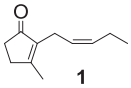
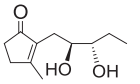
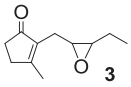
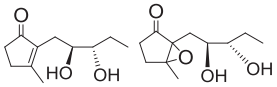
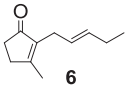
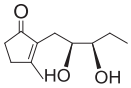
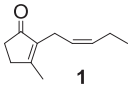
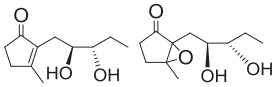
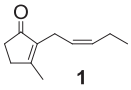
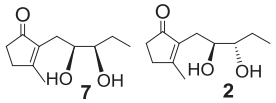
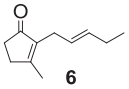
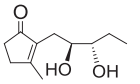
In this work, we study the preparative significance of the *cis*-dihydroxylation of alkenes by using the non-heme iron complexes Fe(**bpmen**)(OTf)**$_2$** **I** (**bpmen**: bispicolyl-*N*,*N*′-methylenthylenendiamine) and Fe(**tpa**)(OTf)$_2$ **II** (**tpa**: tripicolylamine. −OTf: trifluoromethanesulphonate) (Fig. 1).

2. Results and discussion

Use of the **bpmen** system (**I**, Fig. 1) in epoxidation reactions for preparative purposes was first described by Jacobsen.[22a] Later, the oxidation of olefins to *cis*-diols by using **tpa** catalysts (**II**, Fig. 1) under conditions of limiting substrate was described by Que and Nam to have high conversion efficiency; however, these authors worked on substrates with a 0.12 mmol scale. Although some epoxide was also generated, those complexes represented the first examples of iron catalysts capable of olefin *cis*-hydroxylation.[38]

We chose the *cis*-jasmone **1** as a peculiar and interesting substrate because its structure contains both a rich *cis*-alkene and a cyclic deactivated double bond. The oxidation of **1** (0.5 mmol) in the open air with hydrogen peroxide (1.2 equiv) in the presence of Fe(**bpmen**)(OTf)$_2$ (5 mol %) in CH_3CN at room temperature proved to be a regio- and stereoselective process. However, it afforded the *threo* diol **2** as the only oxidation product with 80% yield and 94% conversion (Table 1, entry 1). Furthermore, when the concentration of the catalyst was decreased to 0.2 mol %, the conversion of the oxidation reaction fell to 10% and, again, the diol **2** was obtained but in only 6% yield (Table 1, entry 2). After several attempts, it was clear that the preparative relevance of the process depended on the catalyst concentration, and optimal results were obtained for catalyst concentration values of 5 mol %. When the reaction was run under an inert atmosphere (Ar), we did not observe any substantial

Table 1
Iron (II) complex-catalyzed dihydroxylation of (*Z*)-Jasmone and (*E*)-Jasmone. Studies of the competition between dihydroxylation and epoxide hydrolytic cleavage

Entry	Substrate	Catalyst	Method[a]	Conversion (%)[b]	Products (yield %)[c]
1	 **1**	Fe(**bpmen**)(OTf)$_2$	A	94%	 **2** (80%)
2	 **1**	Fe(**bpmen**)(OTf)$_2$	D	10%	 **2** (6%)
3	 **1**	Fe(**bpmen**)(OTf)$_2$	A[d]	90%	 **2** (79%)
4	 **3**	Fe(**bpmen**)(OTf)$_2$	A	100%	 **2** (12%) **4** (50%)
5	 **6**	Fe(**bpmen**)(OTf)$_2$	A	100%	 **7** (70%)
6	 **1**	Fe(**bpmen**)(OTf)$_2$	C	100%	 **2** (30%) **4** (30%)
7	 **1**	Fe(**tpa**)(OTf)$_2$	A	85%	 **7** + **2** (70%) ***erythro:threo*** = **2:1**
8	 **6**	Fe(**tpa**)(OTf)$_2$	A	75%	 **2** (80%)

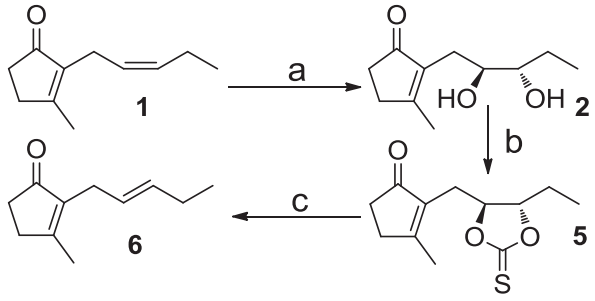
[a] The different procedures (A–D) are described in Experimental section. Typical experiments were performed using 0.5 mmol of starting material. Additionally, most of the tests were carried out at a scale of 2 mmol in order to test the preparative scale of the methodology.
[b] Conversion was determined by GC or ^{1}H NMR analysis of the crude product.
[c] Isolated yield based on the starting substrate.
[d] The reaction was carried under a nitrogen atmosphere.

change in our primary results and hence autooxidation could be ruled out (Table 1, entry 3). These results are different from those obtained previously by Costas and Beller[39] with Me_2PyTACN catalysts (**III**, Fig. 1.) under conditions in which the olefin was not used in large amounts (substrate 0.05 mmol scale) but instead was the limiting reagent.

Working on a substrate at a scale of 0.5 mmol, we have previously reported the anomalous stereochemical outcome of this oxidation reaction as being due either to the water-assisted hydrolytic cleavage of the epoxide precursor **3** or to the participation of carbon-centered radical oxidized olefin species capable of fast epimerization, leading to the most stable intermediate and hence to the *threo* diol **2**.[43]

We were not very confident about our first proposal, since the stereochemical outcome of the dihydroxylation process catalyzed by these types of iron(II) complex is generally linked to an oxo-hydroxy iron(V) species and its interaction with olefins through a concerted [3+2]-cycloaddition mechanism between Fe^{V}(**bpmen**)(O)(OH) and alkenes, which is strongly supported by DFT calculations.[1] No previous references were found in the literature regarding the isolation of *trans*-diols as major products under non-heme iron-catalyzed reaction conditions; nevertheless, the instability of the *cis* epoxide **3** may have been enhanced by the increased concentration of the iron complex, mostly due to its Lewis-acid character. Additionally, when the *cis*-epoxide **3** was allowed to react under the same oxidizing reaction conditions (Table 1, entry 4), two products, **2** and **4**, were obtained with 12% and 50% yields, respectively. Both products exhibited the *threo*-diol functionality in the open chain, which obviously helps to support the hydrolytic cleavage of the epoxide **3** under the reaction conditions.

In order to test the suitability of our second proposal, based on the fast epimerization of a carbon-centered radical intermediate,[43] we decided to perform the oxidation of *trans*-jasmone **6** with hydrogen peroxide in the presence of Fe(**bpmen**)$(OTf)_2$. The synthesis of **6** was achieved by applying a three-step reaction sequence with 60% overall yield (Scheme 1).



Scheme 1. Synthesis of (*E*)-Jasmone using the Corey–Winters method. a) Fe(bpmen)$(OTf)_2$ (5 mol %), H_2O_2 (1.2 equiv), CH_3CN, 10 min at room temperature, (yield: 80%). b) *N*–*N*′-thiocarbonyldiimidazole (1.1 equiv), THF, 20 h at reflux, (yield: 100%). c) $P(OEt)_3$, 20 h at reflux, (yield: 75%).

Treatment of **2** with *N*,*N*′-thiocarbonyldiimidazole in refluxing THF led to the thiocarbonate **5** in quantitative yields. Finally, the reaction of **5** with triethyl phosphite under reflux with the Corey-Winter protocol[47] afforded the *trans*-jasmone **6** with 75% yield.[48]

The oxidation of **6** with hydrogen peroxide (1.2 equiv) in the presence of Fe(**bpmen**)$(OTf)_2$ (5 mol %) in CH_3CN at room temperature led to the *erythro* diol **7** in 70% yield (Table 1, entry 5).[49] This experiment clearly demonstrated that the stereochemical outcome of the oxidation reaction was due to the water-assisted cleavage of the epoxide **3**, since if the participation of an oxidized olefin species capable of fast epimerization were correct, it would have also afforded the *threo* diol **2**, and this was not the case.

The use of oxone (1 equiv) as the terminal oxidant in the oxidation of *cis*-jasmone **1** took place with 100% conversion and afforded a mixture of the *threo* diol **2**, and the epoxide diol **4**, both in 30% yield (Table 1, entry 6).

A change of catalyst to Fe(**tpa**)$(OTf)_2$ allowed us to test the oxidation of **1** when hydrogen peroxide (1.2 equiv) was used as the terminal oxidant. The oxidation process afforded a mixture of *erythro* (**7**) and *threo* (**2**) diols in a 2:1 ratio, respectively, with 85% conversion and 70% yield (Table 1, entry 7). In this context, the use of the **tpa** complex apparently increased the formation of the expected *cis*-dihydroxylation product, the *erythro* diol **7**, and reduced the formation of both the epoxide **3** and of its water-assisted cleavage product **2** in comparison with previous results obtained with Fe(**bpmen**)$(OTf)_2$. Under identical conditions, the *trans*-jasmone **6** led stereoselectively to the *cis*-dihydroxylation product, the *threo* diol **2**, with 75% conversion and 65% yield (Table 1, entry 8). This transformation proved to be the method of choice to obtain the *threo*-diol **2** from *trans*-jasmone **6** through a *cis*-dihydroxylation process.

The use of electron-rich alkenes such as *cis*-3-hexen-1-ol pivalate **8** provides excellent stereoselectivity towards *cis*-dihydroxylation. The oxidation of **8** with hydrogen peroxide (1.2 equiv) in the presence of Fe(**tpa**)$(OTf)_2$ (5 mol %) afforded the *erythro*-diol **9** stereoselectively, with 84% conversion and 80% yield (Table 2, entry 1). Good *cis*-dihydroxylation chemoselectivity has been obtained with e-poor olefins at low substrate conversions, but not with an e-rich olefin under preparative conditions.[38] However, the use of Fe(**bpmen**)$(OTf)_2$ as catalyst under identical conditions afforded a mixture of the epoxide **10** and the *threo*-diol **11**, with 24% and 53% yield, respectively (Table 2, entry 2).

Table 2
Oxidation of electron-rich and deactivated olefins by non-heme iron (II) complexes

Entry	Substrate	Catalyst	Method[a]	Conversion (%)[b]	Products (yield %)[c]
1	**8**	Fe(**tpa**)$(OTf)_2$	A	84%	**9** (81%)
2	**8**	Fe(**bpmen**)$(OTf)_2$	A	100%	**10** (24%)+**11** (53%)
3	**12**	Fe(**tpa**)$(OTf)_2$	A	66%	**13** (7%)+**14** (50%)
4	**12**	Fe(**bpmen**)$(OTf)_2$	A	100%	**13** (50%)+**15** (15%)
5	**16**	Fe(**tpa**)$(OTf)_2$	A	35%	**17** (20%)
6	**16**	Fe(**bpmen**)$(OTf)_2$	A	78%	**18** (75%)
7	**19**	Fe(**tpa**)$(OTf)_2$	A	32%	**20** (30%)
8	**19**	Fe(**bpmen**)$(OTf)_2$	A	40%	**20** (25%)
9	**21**	Fe(**tpa**)$(OTf)_2$	A	50%	**22** (10%)+**23** (18%)
10	**21**	Fe(**tpa**)$(OTf)_2$	A	75%	**22** (28%)+**23** (20%)
11	**24**	Fe(**tpa**)$(OTf)_2$	A	70%	**25** (5%)+**26** (8%) +**27** (28%)

[a] The different procedures are described in Experimental section. Typical experiments were performed using 0.5 mmol of starting material. Most of the tests were carried out at a scale of 2 mmol in order to test the preparative scale of the methodology.
[b] Conversion was determined by GC or ^{1}H NMR analysis of the crude product.
[c] Isolated yield based on the starting substrate.

Again, the major product of the mixture was the water-assisted cleavage product of the epoxide **10**, the *threo*-diol **11**.

By using either Fe(**tpa**)$(OTf)_2$ or Fe(**bpmen**)$(OTf)_2$ as catalysts for the oxidation of *cis*-3-hexen-1-ol benzoate **12**, we obtained mixtures of the epoxide **13** (7%) and the *erythro*-diol **14** (50%) with 66% conversion in the first case, and a mixture of the epoxide **13** (50%) and the *threo*-diol **15** (15%) in the second case (Table 2, entries 3 and 4). With *cis*-4-hexen-1-ol benzoate **16**, oxidation under analogous conditions using the **tpa** ligand afforded the *erythro* isomer **17** exclusively, with 20% yield (35% conversion), but led to the isolation of epoxide **18** with 75% yield (78% conversion) with the bpmen ligand.

Clearly, the **tpa** ligand appears to be the best choice to achieve the *cis*-dihydroxylation of electron-rich alkenes (Table 2, entries 1, 3 and 5).

In the case of electron-poor alkenes, the oxidation of diethyl maleate **19** with hydrogen peroxide (1.2 equiv) afforded the *erythro* diol **20** exclusively, both with the **tpa** (30% yield, 32% conversion) and the **bpmen** (25% yield, 40% conversion) ligands (Table 2, entries 7 and 8).

In the case of 4,9(11)-androstadien-3,17-dione **21**, oxidation with hydrogen peroxide (1.2 equiv) in the presence of Fe(**tpa**)$(OTf)_2$ afforded a mixture of the epoxide **22** and the allylic alcohol **23** with 10% and 18% yields, respectively, with 50% conversion. Increasing the concentration of the catalyst (15 mol %) and the terminal oxidant hydrogen peroxide (3.6 equiv) led to the same mixture of compounds **22** and **23** with 28% and 20% yields, respectively, with 75% conversion (Table 2, entries 9 and 10) (Fig. 2).

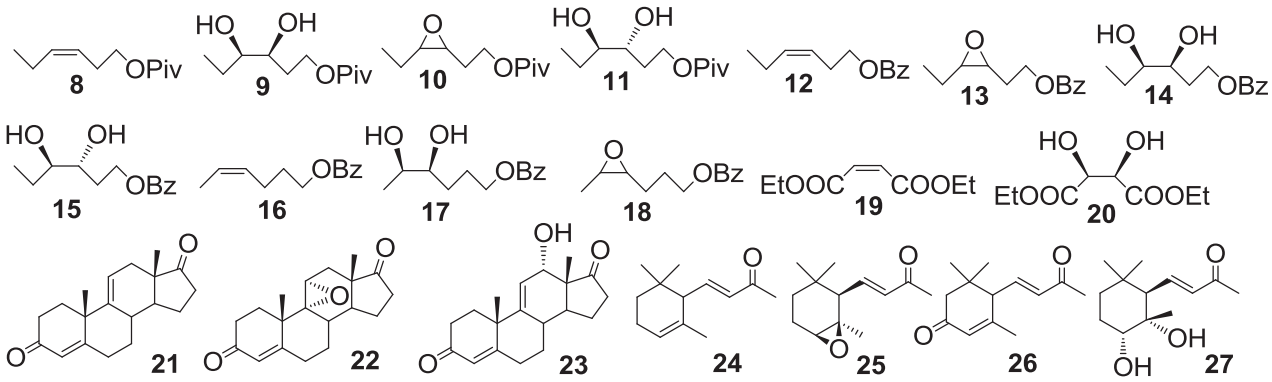


Fig. 2. Substrates and products from comparative studies between electron-poor and electron-rich olefins.

Finally, oxidation of the α-ionone **24** afforded a mixture of the epoxide **25** (5% yield), the enone **26** (8%) and *cis* diol **27** (28%) with 70% conversion (Table 2, entry 11). Structural assessment of *cis*-diol **27** was achieved through complete NMR analysis of the product and by comparison of the spectroscopic data with those described for the same compound in the literature.[50]

3. Conclusions

The preparative relevance of the non-heme iron-catalyzed *cis*-dihydroxylation of alkenes with hydrogen peroxide in the presence of Fe(**bpmen**)$(OTf)_2$ and Fe(**tpa**)$(OTf)_2$ is linked to the catalyst concentration, the optimal catalyst concentration being 5 mol %. However, at these concentration values, the Fe(**bpmen**)$(OTf)_2$ catalyst mostly gave rise to mixtures of epoxides and the *threo*-diols formed by water-assisted hydrolytic cleavage of the epoxides.

The Fe(**tpa**)$(OTf)_2$ complex always gave the *cis*-dihydroxylation products as the major products in mixtures with the epoxides, and in some cases (with e-rich (**8**) and deactivated (**19**) olefins) gave the *cis*-dihydroxylation products (**9** and **20**) exclusively.

When deactivated olefins were used as substrates for the non-heme iron-catalyzed oxidation of alkenes, *cis*-diols were obtained exclusively, although with modest conversions, regardless of the catalyst used in the transformations.

4. Experimental section

4.1. General experimental methods

^1H NMR spectra were measured at either 200 or 400 MHz and ^{13}C NMR were measured at 50 or 100 MHz in CDCl3 and referenced to TMS (^1H) or solvent (^{13}C) except where indicated otherwise. HRMS determinations were recorded at the Mass Spectrometry Service of the University of Salamanca, Spain, on an Applied Biosystems QSTAR XL with ESI ionization. The GC–MS analysis of the reaction mixtures was performed using a Agilent MS 220 gas chromatograph and a GC7890A selective mass detector. A DB5 column was used (30 m long, 0.25 mm internal diameter and 0.25 μm layer thickness), with helium as the carrier gas. The sampling program started at 50 °C as the initial temperature, and after 5 min the temperature was raised to 270 °C with a gradient of 10 °C/min, and was held for an additional 5 min. The components of the mixtures were identified by comparing their full mass spectra and retention times with the corresponding data for reference compounds at the National Institute of Standard Technologies database (NIST 2011). The chemicals and solvents used were obtained from commercial sources and used as received with the exception of tetrahydrofuran, which was distilled from sodium and benzophenone. H_2O_2 was titrated with $KMnO_4$ previously normalized using $K_2C_2O_4$ as a primary standard. Unless specified otherwise, the reported yields are for chromatographically pure isolated products. Preparation of the catalysts Fe(**bpmen**)$(OTf)_2$ **I** and Fe(**tpa**)$(OTf)_2$ **II** was achieved as described in the literature.[45] Protocols A–C are described at a starting material scale of 0.5 mmol. No changes in the yields or reaction products were observed when a starting material scale of 2 mmol was tested.

4.2. Protocol A (5 mol % of catalyst)

A 10 mL round-bottomed flask was loaded with 0.75 mL of CH_3CN, catalyst (0.025 mmol, 5 mol %), and substrate (0.5 mmol, 1.0 equiv). The solution was stirred vigorously at room temperature. A 0.13 M solution of H_2O_2 in CH_3CN (4 mL, 1.2 equiv) was added dropwise via a syringe. After the addition had been completed, the reaction mixture was stirred for an additional 10 min. Then, a saturated aqueous $NaHCO_3$ solution was added and the mixture was extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, evaporated under reduced pressure, and purified by flash chromatography.

4.3. Iterative protocol B (15 mol % of catalyst)

A 50 mL round-bottomed flask was loaded with 0.75 mL of CH_3CN, catalyst (0.025 mmol, 5 mol %), and substrate (0.5 mmol, 1.0 equiv). The solution was stirred vigorously at room temperature. A 0.13 M solution of H_2O_2 in CH_3CN (4 mL, 1.2 equiv) was added dropwise via a syringe. After stirring for 10 min, 0.5 mL of CH_3CN and catalyst (0.025 mmol, 5 mol %) was added. This was followed by dropwise addition of H_2O_2 (30 wt %, 68 μL, 0.6 mmol, 1.2 equiv) in CH_3CN (4 mL, 0.13 M). A third addition was performed for a total of 15 mol % catalyst and 3.6 equiv of H_2O_2. After the last 10 min of

stirring, $NaHCO_3$-saturated aqueous solution was added and the mixture was extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, evaporated under reduced pressure, and purified by flash chromatography.

4.4. Protocol C

A 50 mL round-bottomed flask was loaded with substrate (0.5 mmol, 1.0 equiv), 7.5 mL of CH_3CN, 5.0 mL of H_2O, Oxone (0.5 mmol, 1.0 equiv) and catalyst (0.025 mmol, 5 mol %). The solution was stirred and heated at 80 °C for 6 h. Then, the solution was filtered and the filtrate was extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na_2SO_4, evaporated under reduced pressure, and purified by flash chromatography.

4.5. Protocol D

In order to perform this experiment we followed the method of Que et al. *JACS*, **2003**, *125*, 9912–9913.[46]

Compounds (±)**2** and **4** (as a mixture of diastereoisomers) are described in reference *n*°43.

Compounds **22**, **23**, and **25** are described in reference *n*°42.

4.6. *Trans*-jasmone 6

^{1}H NMR ($CDCl_3$): δ=0.92 (t, J_1=7 Hz, 3H), 1.27 (m, 2H), 1.95 (m, 2H), 2.04 (s, 3H), 2.35 (dd, J_1=5 Hz, J_2=4 Hz, 1H), 2.49 (m, 1H), 2.86 (d, J_1=6 Hz, 2H), 5.36 (m, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=13.9 (q), 17.4 (q), 25.6 (t), 26.2 (t), 31.8 (t), 34.5 (t), 125.1 (d), 133.1 (d), 139.1 (s), 171.1 (s), 209.3 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{11}H_{16}ONa$: 187.1093, experimental: 187.1094.

4.7. 2-[(2*SR*,3*RS*)-2,3-Dihydroxypentyl]-3-methylcyclopent-2-enone (±)7

^{1}H NMR ($CDCl_3$): δ=0.92 (t, J=7 Hz, 3H), 1.48 (m, 2H), 2.11 (s, 3H), 2.53 (m, 4H), 3.38 (m, 2H), 3.58 (m, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.4 (q), 17.8 (q), 25.6 (t), 26.3 (t), 32.5 (t), 34.3 (t), 74.0 (d), 75.0 (d), 138.0 (s), 174.9 (s), 212.8 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{11}H_{18}O_3Na$: 221.1148, experimental: 221.1147.

4.8. (3*SR*,4*RS*)-3,4-Dihydroxyhexyl pivalate (±)9

^{1}H NMR ($CDCl_3$): δ=0.96 (t, J=8 Hz, 3H), 1.16 (s, 9H), 1.45 (m, 2H), 1.73 (m, 2H), 3.58 (m, 1H), 4.20 (m, 2H), 4.31 (m, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.5 (q), 25.0 (t), 27.4 (q, 3C), 30.3 (t), 39.0 (s), 61.9 (t), 71.1 (d), 76.1 (d), 179.3 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{11}H_{22}O_4Na$: 241.1410, experimental: 241.1405.

4.9. 2-[(2*SR*,3*RS*)-3-Ethyloxiran-2-yl]ethyl pivalate (±)10

^{1}H NMR ($CDCl_3$): δ=1.05 (t, J=7 Hz, 3H), 1.18 (s, 9H), 1.58 (m, 2H), 1.87 (m, 2H), 2.92 (m, 1H), 3.00 (m, 1H), 4.22 (t, J=7 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.8 (q), 21.3 (t), 27.2 (q, 3C), 27.6 (t), 38.9 (s), 54.4 (d), 58.2 (d), 62.1 (t), 178.7 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{11}H_{21}O_3$: 201.1485, experimental: 201.1480.

4.10. (3*RS*,4*RS*)-3,4-Dihydroxyhexyl pivalate (±)11

^{1}H NMR ($CDCl_3$): δ=0.99 (t, J=7 Hz, 3H), 1.20 (s, 9H), 1.45 (m, 2H), 1.73 (m, 2H), 3.39 (m, 1H), 3.50 (m, 1H), 4.20 (m, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.0 (q), 26.5 (t), 27.4 (q, 3C), 33.2 (t), 39.0 (s), 61.6 (t), 70.9 (d), 75.9 (d), 179.3 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{11}H_{22}O_4Na$: 241.1410, experimental: 241.1403.

4.11. 2-[(2*SR*,3*RS*)-3-Ethyloxiran-2-yl]ethyl benzoate (±)13

^{1}H NMR ($CDCl_3$): δ=1.05 (t, J=8 Hz, 3H), 1.56 (m, 2H), 1.98 (m, 2H), 2.92 (dt, J_1=7 Hz, J_2=4 Hz, 1H), 3.12 (dt, J_1=6 Hz, J_2=5 Hz, 1H), 4.50 (t, J=7 Hz, 2H), 7.43 (dd, J_1=7 Hz, J_2=5 Hz, 2H), 7.57 (d, J=5 Hz, 1H), 8.06 (d, J=7 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.8 (q), 21.3 (t), 27.8 (t), 54.6 (d), 58.3 (d), 62.6 (t), 128.6 (d, 2C), 129.8 (d, 2C), 130.3 (s), 133.2 (d), 166.7 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{16}O_3Na$: 243.0991, experimental: 243.0987.

4.12. (3*SR*,4*RS*)-3,4-Dihydroxyhexyl benzoate (±)14

^{1}H NMR ($CDCl_3$): δ=0.95 (t, J=7 Hz, 3H), 1.46 (m, 2H), 1.90 (m, 2H), 3.58 (m, 1H), 3.74 (m, 1H), 4.46 (m, 2H), 7.39 (dd, J_1=7 Hz, J_2=5 Hz, 2H), 7.49 (d, J=5 Hz, 1H), 8.00 (d, J=7 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.6 (q), 24.9 (t), 30.5 (t), 62.6 (t), 71.2 (d), 76.3 (d), 128.6 (d, 2C), 129.8 (d, 2C), 130.3 (s), 133.3 (d), 167.2 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{18}O_4Na$: 261.1097, experimental: 261.1088.

4.13. (3*RS*,4*RS*)-3,4-Dihydroxyhexyl benzoate (±)15

^{1}H NMR ($CDCl_3$): δ=0.95 (t, J=7 Hz, 3H), 1.46 (m, 2H), 1.90 (m, 2H), 3.58 (m, 1H), 3.74 (m, 1H), 4.46 (m, 2H), 7.39 (dd, J_1=7 Hz, J_2=5 Hz, 2H), 7.49 (d, J=5 Hz, 1H), 8.00 (d, J=7 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=10.1 (q), 26.6 (t), 29.9 (t), 62.2 (t), 71.0 (d), 76.0 (d), 128.6 (d, 2C), 129.8 (d, 2C), 130.2 (s), 133.3 (d), 167.3 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{18}O_4Na$: 261.1097, experimental: 261.1084.

4.14. (4*S*,5*R*)-4,5-Dihydroxyhexyl benzoate (±)17

^{1}H NMR ($CDCl_3$): δ=1.17 (t, J=6.2 Hz, 3H), 1.49–2.06 (m, 4H), 2.44 (br s, 2H), 3.64 (m, 1H), 3.80 (m, 1H), 4.36 (t, J=6.6 Hz, 2H), 7.40 (dd, J_1=7 Hz, J_2=5 Hz, 2H), 7.55 (d, J=5 Hz, 1H), 8.02 (d, J=7 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=17.0 (q), 25.7 (t), 28.3 (t), 65.1 (t), 70.7 (d), 74.7 (d), 128.6 (d, 2C), 129.7 (d, 2C), 130.4 (s), 133.2 (d), 167.0 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{18}O_4Na$: 261.1097, experimental: 261.1101.

4.15. 3-(3-Methyloxiran-2-yl)propyl benzoate (±)18

^{1}H NMR ($CDCl_3$): δ=3.02 (m, 2H), 4.36 (t, J=6.8 Hz, 2H), 7.41 (dd, J_1=7.2 Hz, J_2=6.4 Hz, 2H), 7.50 (d, J=6.4 Hz, 1H), 8.02 (d, J=7.2 Hz, 2H) ppm. ^{13}C NMR ($CDCl_3$): δ=24.0 (q), 25.9 (t), 28.8 (t), 53.1 (d), 56.9 (d), 64.7 (t), 128.6 (d, 2C), 129.7 (d, 2C), 130.3 (s), 133.2 (d), 166.9 (s) ppm. ESI-HRMS (M+H): calculated for $C_{13}H_{17}O_3$: 221.1172, experimental: 221.1181.

4.16. (2*RS*,3*SR*)-Diethyl 2,3-dihydroxysuccinate 20

^{1}H NMR ($CDCl_3$): δ=1.30 (t, J_1=7 Hz, 3H), 3.20 (br s, 1H), 4.26 (m, 2H), 4.55 (s, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ=14.3 (q), 62.5 (t), 73.1 (d), 171.3 (s) ppm. ESI-HRMS (M+Na): calculated for $C_8H_{14}O_6Na$: 229.0682, experimental: 229.0681.

4.17. (*E*)-3,5,5-Trimethyl-4-(3-oxobut-1-en-1-yl)cyclohex-2-enone 26

^{1}H NMR ($CDCl_3$): δ=0.99 (s, 3H), 1.06 (s, 3H), 1.88 (s, 3H), 2.12 (d, J=16.8 Hz, 1H), 2.26 (s, 3H), 2.35 (d, J=16.8 Hz, 1H), 2.69 (d, J=9.4 Hz, 1H), 5.97 (s, 1H), 6.17 (d, J=15.6 Hz, 1H), 6.65 (dd, J_1=9.4 Hz, J_2=15.6, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ=23.7 (q), 27.5 (q), 27.8 (q), 28.1 (q), 36.9 (s), 47.5 (t), 55.6 (t), 127.1 (d), 133.9 (d), 143.8 (d), 159.4 (s), 197.8 (s), 198.6 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{18}O_2Na$: 229.1199, experimental: 229.1201.

4.18. (*E*)-4-((2*R*,3*S*)-2,3-Dihydroxy-2,6,6-trimethylcyclohexyl) but-3-en-2-one 27

^{1}H NMR ($CDCl_3$): δ=0.78 (s, 3H), 1.05 (s, 3H), 1.14 (s, 3H), 2.10 (d, J=10.6 Hz, 1H), 2.30 (s, 3H), 3.58 (d, J=3.2 Hz, 1H), 6.08 (d, J=16.0 Hz, 1H), 6.96 (dd, J_1=10.6 Hz, J_2=16.0, 1H) ppm. ^{13}C NMR ($CDCl_3$): δ=22.4 (q), 25.4 (t), 27.2 (q), 28.3 (q), 32.4 (q), 33.8 (t), 34.1 (s), 53.4 (d), 73.6 (s), 74.6 (d), 135.0 (d), 146.9 (d), 198.9 (s) ppm. ESI-HRMS (M+Na): calculated for $C_{13}H_{22}O_3Na$: 249.1461, experimental: 249.1468.

Acknowledgements

We are grateful to Takasago International Chemicals (Europe) SA, El Palmar, Murcia, Spain for the generous gift of *cis*-jasmone. Also, D.C.T. wishes to thank the F.S.E. and the Consejería de Educación de la Junta de Castilla y León for a predoctoral grant.

Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2014.10.037.

References and notes

1. Sugimoto, H.; Kitayama, K.; Mori, S.; Itoh, S. *J. Am. Chem. Soc.* **2012**, *134*, 19270–19280.
2. (a) Mayer, A. C.; Bolm, C. In *Iron Catalysis in Organic Chemistry*; Plietker, B., Ed.; Wiley-VCH: Weinheim, Germany, 2008; pp 73–92; (b) Oldenburg, P. D.; Mas-Ballesté, R.; Que, L., Jr. In *Mechanisms in Homogeneous and Heterogeneous Epoxidation Catalysis*; Oyama, S. T., Ed.; Elsevier: Amsterdam, 2008; pp 451–469; (c) Company, A.; Gómez, L.; Costas, M. In *Iron-containing Enzymes: Versatile Catalysts of Hydroxylation Reactions in Nature*; de Viser, S. P., Kumar, D., Eds.; Royal Society of Chemistry: London, UK, 2011; pp 148–208; (d) Bryliakov, K. P.; Talsi, E. P. *Coord. Chem. Rev.* **2014**, *276*, 73–96.
3. Chen, K.; Que, L. *J. Am. Chem. Soc.* **2001**, *123*, 6327–6337.
4. Kim, C.; Chen, K.; Kim, J.; Que, L. *J. Am. Chem. Soc.* **1997**, *119*, 5964–5965.
5. Costas, M.; Que, L. *Angew. Chem., Int. Ed.* **2002**, *41*, 2179–2181.
6. Van den Berg, T. A.; de Boer, J. W.; Browne, W. R.; Roelfes, G.; Feringa, B. L. *Chem. Commun.* **2004**, 2550–2551.
7. England, J.; Britovsek, G. J. P.; Rabadia, N.; White, A. J. P. *Inorg. Chem.* **2007**, *46*, 3752–3767.
8. Roelfes, G.; Lubben, M.; Hage, R.; Que, L.; Feringa, B. L. *Chem.—Eur. J.* **2000**, *6*, 2152–2159.
9. Chen, K.; Que, L. *Chem. Commun.* **1999**, 1375–1376.
10. (a) McDonald, A. R.; Que, L., Jr. *Nat. Chem.* **2011**, *3*, 761–762; (b) Prat, I.; Mathieson, J. S.; Güell, M.; Ribas, X.; Lui, J. M.; Cronin, L.; Costas, M. *Nat. Chem.* **2011**, *3*, 788–793.
11. Nguyen, C.; Guajardo, R. J.; Mascharak, P. K. *Inorg. Chem.* **1996**, *35*, 6273–6281.
12. Rowland, J. M.; Olmstead, M.; Mascharak, P. K. *Inorg. Chem.* **2001**, *40*, 2810–2817.
13. Godbole, M. D.; Puig, M. P.; Tanase, S.; Kooijman, H.; Spek, A. L.; Bouwman, E. *Inorg. Chim. Acta* **2007**, *360*, 1954–1960.
14. Li, F.; Wang, M.; Ma, C.; Gao, A.; Chen, H.; Sun, L. *Dalton Trans.* **2006**, 2427–2434.
15. Romakh, V. B.; Therrien, B.; Süss-Fink, G.; Shulpin, G. B. *Inorg. Chem.* **2007**, *46*, 3166–3175.
16. Gutkina, E. A.; Trukhan, V. M.; Pierpont, C. P.; Mkoyan, S.; Strelets, V. V.; Nordlander, E.; Shteinman, A. A. *Dalton Trans.* **2006**, 492–501.
17. Suh, Y.; Seo, M. S.; Kim, K. M.; Kim, Y. S.; Jang, H. G.; Tosha, T.; Kitagawa, T.; Kim, J.; Nam, W. J. *Inorg. Biochem.* **2006**, *100*, 627–633.
18. Lane, B. S.; Burgess, K. *Chem. Rev.* **2003**, *103*, 2457–2474.
19. (a) Ono, M.; Okura, I. *J. Mol. Catal.* **1990**, *61*, 113–122; (b) Burger, R. M. *Chem. Rev.* **1998**, *98*, 1153–1170.
20. Nam, W.; Ho, R.; Valentine, J. S. *J. Am. Chem. Soc.* **1991**, *113*, 7052–7054.
21. Guajardo, R. J.; Hudson, S. E.; Brown, S. J.; Mascharak, P. K. *J. Am. Chem. Soc.* **1993**, *115*, 7971–7977.
22. (a) White, M. C.; Doyle, A. G.; Jacobsen, E. *J. Am. Chem. Soc.* **2001**, *123*, 7194–7195; (b) Chen, M. S.; White, C. *Science* **2007**, *318*, 783–787; (c) Vermeulen, N. A.; Chen, M. S.; White, C. *Tetrahedron* **2009**, *65*, 3078–3084; (d) Chen, M. S.; White, C. *Science* **2010**, *327*, 566–567; (e) Bigi, M. A.; Reed, S.; White, C. *Nat. Chem.* **2011**, *3*, 216–222; (f) Bigi, M. A.; Reed, S.; White, C. *J. Am. Chem. Soc.* **2012**, *134*, 9721–9726.
23. Duban, E. A.; Bryliakov, K. P.; Talsi. *Eur. J. Inorg. Chem.* **2007**, 852–857.
24. Fujita, M.; Que, L. *Adv. Synth. Catal.* **2004**, *346*, 190–194.
25. Dubois, G.; Murphy, A.; Stack, T. D. P. *Org. Lett.* **2003**, *5*, 2469–2472.
26. Quinonero, D.; Musaev, D. G.; Morokuma, K. *Inorg. Chem.* **2003**, *42*, 8449–8455.
27. Mas-Ballesté, R.; Costas, M.; van der Berg, T.; Que, L. *Chem.—Eur. J.* **2006**, *12*, 7489–7500.
28. Bukowski, M. R.; Comba, P.; Lienke, A.; Limberg, C.; Lopez de Laorden, C.; Mas-Ballesté, R.; Merz, M.; Que, L. *Angew. Chem., Int. Ed.* **2006**, *45*, 3446–3449.
29. Taktak, S.; Ye, W.; Herrera, A. M.; Rybak-Akimova, E. V. *Inorg. Chem.* **2007**, *46*, 2929–2942.
30. Gosiewska, S.; Lutz, M.; Spek, A. L.; Klein Gebbink, R. J. M. *Inorg. Chim. Acta* **2007**, *360*, 405–417.
31. Bitterlich, B.; Anilkumar, G.; Gelalcha, F. G.; Spilker, B.; Grotevendt, A.; Jackstell, R.; Tse, M. K.; Beller, M. *Chem.—Asian J.* **2007**, *2*, 521–529.
32. Anilkumar, G.; Bitterlich, B.; Gelalcha, F. G.; Tse, M. K.; Beller, M. *Chem. Commun.* **2007**, 289–291.
33. Gelalcha, F. G.; Bitterlich, B.; Tse, M. K.; Beller, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 7293–7296.
34. Chen, K.; Que, L. *Angew. Chem., Int. Ed.* **1999**, *38*, 2227–2229.
35. Costas, M.; Tipton, A. K.; Chen, K.; Jo, D.-H.; Que, L. *J. Am. Chem. Soc.* **2001**, *123*, 6722–6723.
36. (a) Chen, K.; Costas, M.; Kim, J.; Tipton, A. K.; Que, L. *J. Am. Chem. Soc.* **2002**, *124*, 3026–3035.
37. (a) Chen, K.; Costas, M.; Que, L. *J. Chem. Soc., Dalton Trans.* **2002**, 672–679; (b) Barry, S. M.; Mueller-Bunz, H.; Rutledge, P. J. *Org. Biomol. Chem.* **2012**, *10*, 7372–7381.
38. Ryu, J. Y.; Kim, J.; Costas, M.; Chen, K.; Nam, W.; Que, L., Jr. *Chem. Commun.* **2002**, 1288–1289.
39. Prat, I.; Font, D.; Company, A.; Junge, K.; Ribas, X.; Beller, M.; Costas, M. *Adv. Synth. Catal.* **2013**, *355*, 947–956.
40. Que, L., Jr.; Tolman, W. *Nature* **2008**, *455*, 333–340 and references therein.
41. Meunier, B. *Biomimetic Oxidations Catalyzed by Transition Metal Complexes*; Imperial College: London, UK, 2000.
42. Clemente-Tejeda, D.; López-Moreno, A.; Bermejo, F. *Tetrahedron* **2012**, *68*, 9249–9255.
43. Clemente-Tejeda, D.; López-Moreno, A.; Bermejo, F. *Tetrahedron* **2013**, *69*, 2977–2986.
44. López-Moreno, A.; Clemente-Tejeda, D.; Calbo, J.; Naemi, A.; Bermejo, F. A.; Ortí, E.; Pérez, E. M. *Chem. Commun.* **2014**, *50*, 9372–9375, http://dx.doi.org/10.1039/c4cc04026k
45. Diebold, A.; Hagen, K. S. *Inorg. Chem.* **1998**, *37*, 215–223.
46. Fujita, M.; Costas, M.; Que, L., Jr. *J. Am. Chem. Soc.* **2003**, *125*, 9912–9913.
47. Corey, E. J.; Winter, R. A. E. *J. Am. Chem. Soc.* **1963**, *85*, 2677–2678.
48. Barton, D. H. R.; Stick, R. V. *J. Chem. Soc., Perkin Trans. 1* **1975**, 1773–1776.
49. The unequivocal structural assignment of the *cis*-diol (−)-**7** was achieved by the reaction of *cis*-jasmone **1** under Sharpless dihydroxylation conditions, with 76% yield (Ref. 43).
50. (a) Etoh, H.; Ina, K.; Iguchi, M. *Nippon. Nogeik. Kaishi* **1980**, *54*, 279–282; (b) Uebelhart, P.; Baumeler, A.; Haag, A.; Prewo, R.; Bieri, J. H.; Eugster, C. H. *Helv. Chim. Acta* **1986**, *69*, 816–834.